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Planetesimal accretion in binary star systems

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Abstract. Numerical simulations of planetesimal accretion in circumprimary and circumbinary orbits are described. The secular perturbations by the companion star and gas drag are included in our models. We derive limits on the parameters of the binary system for which accretion and then planetary formation are possible. In the circumbinary case we also outline the radial distance from the baricenter of the stars beyond which accumulation always occurs. Hydrodynamical simulations are also presented to validate our N-body approach based on the axisymmetric approximation for the gas of the disk.

1. Formation of planets by core-accretion

The formation of terrestrial planets and cores of giant planets within circumstellar disks involves the accumulation of a large number of planetesimals, solid bodies with initial sizes of roughly several kilometers (Lissauer 1993; Wetherill & Stewart 1993). The initial growth of the planetesimals can follow different paths depending on their mutual velocities. If runaway growth occurs, a limited number of large planetary embryos form on a short timescale (about $10^4 - 10^5$ years) followed by a period of violent mutual collisions until the planets reach their final mass. If the encounter velocities exceed the planetesimal's escape velocities, the size distribution of the entire population exhibits an orderly growth until larger bodies are formed on a much longer timescale.

Most observed extrasolar planets are believed to have formed from planetesimals. The core-accretion model (Pollack et al., 1996) seems to explain a large fraction of the observed physical and dynamical properties of extrasolar gaseous giants in particular after the inclusion of migration by interaction with an evolving disk and gap formation (Alibert et al. (2005)). Neptune-size extrasolar planets possibly formed directly by planetesimal accumulation without reaching the critical mass to accrete a massive gaseous envelope. Around single stars the efficiency of planetesimal accumulation is very high, leading easily to planet formation. The influence of collective perturbations like stirring by

mutual gravitational perturbations and damping by collisions and gas drag effects has been studied in detail in order to understand the conditions favoring runaway growth.

Radial velocity surveys have shown that exoplanets are found also in binary or higher multiplicity stellar systems (Raghavan et al. 2006, Desidera & Barbieri 2007). Planetesimal accumulation and then planet formation in binary (or multiple) stellar systems appears to be a more complex process than around single stars. The gravitational secular perturbations by the companion star may overcome the mutual planetesimal interactions and significantly affect the initial stage of accretion by exciting high eccentricities and then affecting significantly the relative velocity distribution. In this paper we explore the velocity evolution of planetesimals in S or C-type orbits under both, the perturbing effects of the companion star and gas drag. We recall that planetesimals revolving just about one star in a binary pair are on so-called "S-type" or "circumprimary" orbits, whereas those that revolve about both stars have "P-type" or "circumbinary" orbits.

2. The circumprimary case (S-type orbits)

The size distribution of planetesimals evolves via mutual collisions between the bodies. It is crucial that in the early stages of accumulation the relative velocities between the planetesimals remain low. While in a planetesimal swarm around a single star the relative velocities are on average less than the escape velocity of the largest bodies, the relative velocities can be pumped up to values leading to disruption of the impacting bodies when a binary companion is present on an outer orbit. Under this condition, fragmentation would dominate over accretion halting the planetary formation process. We have shown (Marzari & Scholl, 2000) that a crucial role is played by gas drag which damps the eccentricity forced by the binary companion and causes an alignment of the planetesimal perihelia. The resulting phasing of the orbits leads to very low relative velocities between equal size planetesimals. However, once larger planetesimals are formed, the perihelion alignment is not so effective. Different size planetesimals have their orbits oriented towards different directions since the gas friction depends on the body size (Thébault et al., 2006). The forced unpaired orbital alignment may easily re-establish high random velocities thus slowing down or even preventing accretion.

By performing N-body numerical simulations where the orbits of the planetesimals are computed under the influence of the gravitational pull of the companion star and gas drag, we have tested the chances of planetesimal accretion for 120 different binary systems with semimajor axis a_B ranging from 10 to 50 AU and eccentricity from 0.05 to 0.9. The mass ratio between the stars have been kept constant and equal to 0.5. In Fig. 1 we plot the regions in the binary parameter space where accretion is possible via runaway growth (dark green) and probably via orderly growth (light green). The orange and red areas correspond to scenarios where planetesimal accretion is inhibited by high values of relative velocities while the yellow region is an intermediate zone where the tendency towards either accretion or erosion strongly depends on the planetesimal physical parameters.

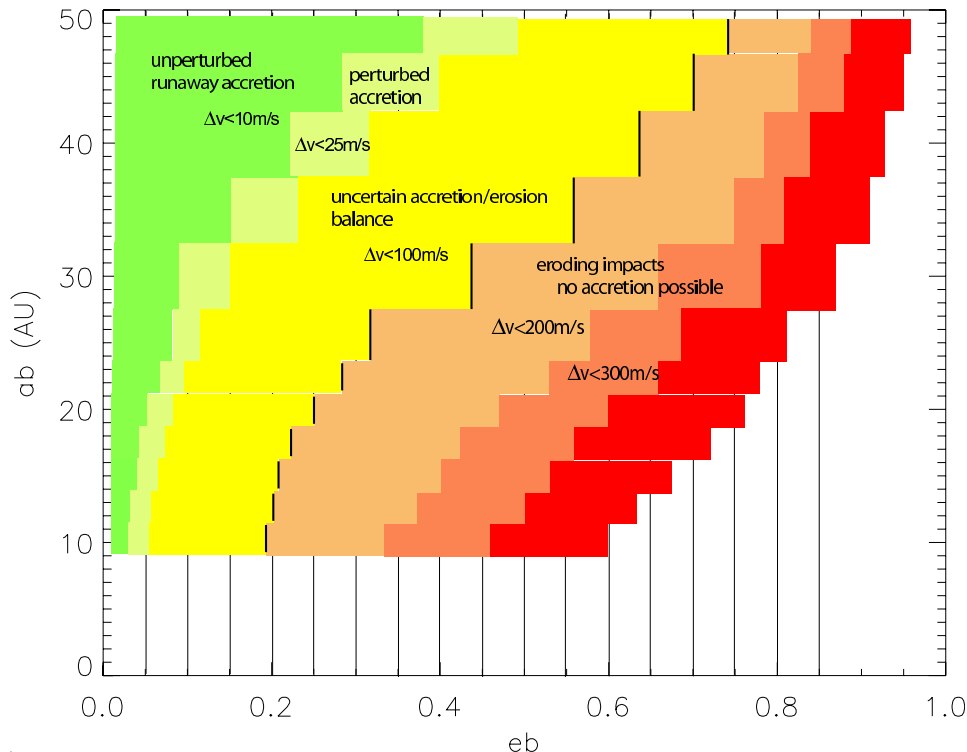


Figure 1. Encounter velocities averaged, over the time interval $0 < t < 2 \times 10^4$ yrs, between $R_1 = 2.5$ and $R_2 = 5$ km bodies at 1 AU from the primary star, for different values of the companion star's semi-major axis and eccentricity. The short black vertical segments mark the limit beyond which $\langle \Delta v_{(R1,R2)} \rangle$ values correspond to eroding impacts for all tested collision outcome prescriptions.

According to Fig. 1 binary star systems with high eccentricity and low separation can hardly allow planetesimal accumulation around the primary star. From the data of the simulations, Thébault et al. (2006) derived an empirical fit that allows to analytically compute the values of binary separation a_B and eccentricity e_B for which accretion is possible:

$$e_b \simeq 0.013 \left(\frac{a_b}{10\text{AU}} \right)^2 \quad (1)$$

By extrapolating the fit to larger values of a_b one can figure out that for binary separation $a_b \gtrsim 90\text{AU}$ the planetesimal accretion process is not significantly perturbed by the companion star gravity.

3. The circumbinary case (P-type orbits)

So far, only one planet, HD 202206c, has been found in a P-type orbit (Udry et al., 2002; Correia et al. 2005). However, this does not imply that circumbinary

planets are rare as to detect such planets by radial velocity measurements is intrinsically difficult due to the short-term large-amplitude velocity of the primary induced by the companion star. Circumbinary material has been found around pre-main-sequence close binaries like DQ Tau or UZ Tau by mid-infrared surveys. The inferred disks are even more massive than the minimum-mass solar nebula suggesting that planet formation may undergo in the standard way. As for the circumpriary case, we have explored planetesimal accumulation in P-type orbits by performing N-body numerical integrations of planetesimals orbits around the barycenter of the binary system. In our model we adopt a simplified approach to compute the gas friction on the bodies by assuming that the gaseous disk is axisymmetric and pressure supported. Taking into account that the tidal force of the binary leads to a gap opening in the inner disk and to spiral density waves propagating through the disk we had to test whether the spiral structure of the gas density might affect the planetesimal trajectories altering the orbital alignment due to gas friction and, in general, changing the planetesimal dynamical evolution. With a hybrid approach, we have computed the evolution of the gaseous component of the disk with an hydrodynamical code (FARGO, Masset 2000) and used the derived local gas density and velocity to calculate the drag force on a limited number of planetesimals embedded in the disk. The limitation in the number of computed planetesimal trajectories is related to the large amount of CPU time required by the hydrodynamical part of the hybrid code. The outcome of a test simulation is given in Fig. 2. We show the evolution of the orbital eccentricity and pericenter of 14 planetesimals with a diameter of 10 km and a density of 2 g/cm^3 with equally spaced initial semimajor axes between 1.2 and 2.5 AU from the barycenter of the stars. The binary system is made of two stars with masses of 0.8 and 0.2 solar masses, respectively, orbiting each other with a semimajor axis of 0.2 AU and an eccentricity of 0.4.

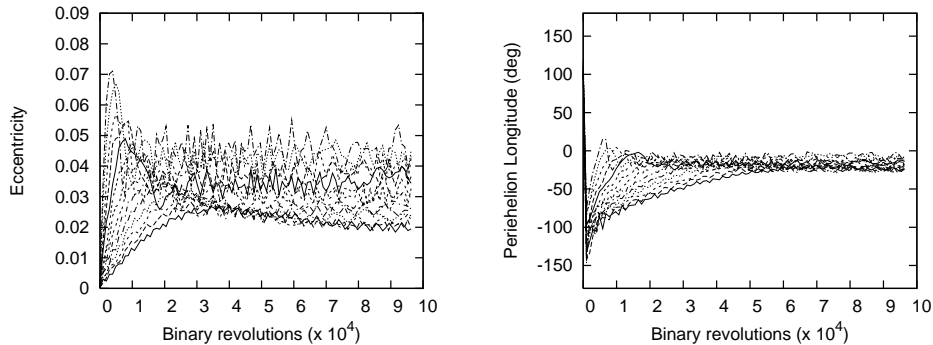


Figure 1. Orbital evolution of 10-km size planetesimals computed with the hybrid code. The eccentricities reach a steady state while the pericenters are well aligned.

The results of the hybrid code are very similar to those obtained with the N-body code where the axisymmetric assumption is adopted.

After the validation of the N-body code, we have considered a more general circumbinary case where the stars are separated by 1 AU and have a total mass of $1 M_{\odot}$. We have integrated the trajectories of 25000 planetesimals with initial semimajor axis ranging from 4 (outside the tidal gap) to 12 AU from the barycenter.

ter of the two stars (Scholl et al., 2007). Taking into account the dependence of the perihelion alignment on the planetesimal size, even in this case we computed relative velocities between representative pairs of different size planetesimals. In Fig. 3 we display, for different binary mass ratios and eccentricities, the minimum radial distance beyond which planetesimal accretion and then planetary formation is possible.

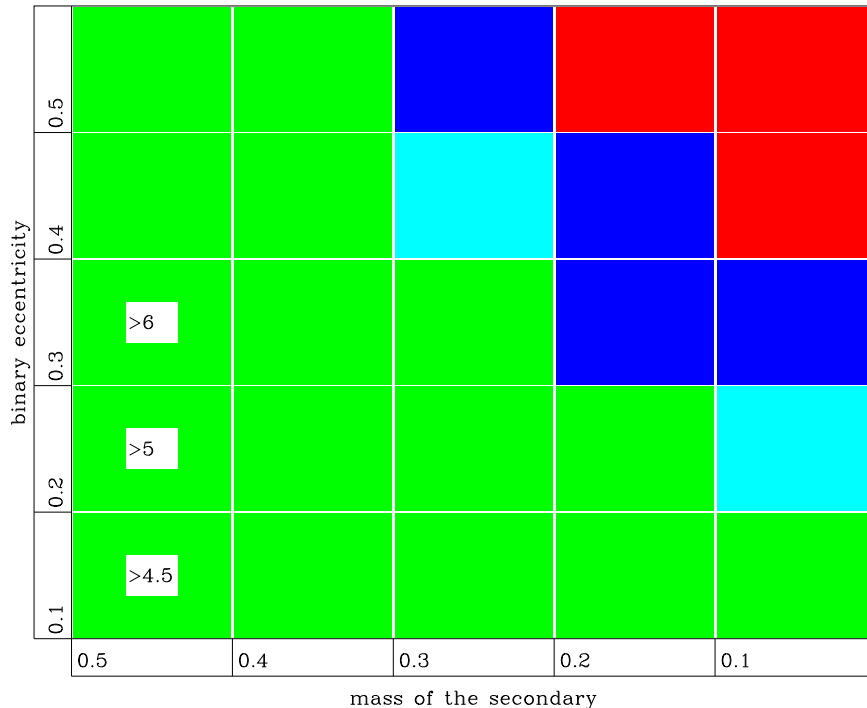


Figure 1. Map of the radial distance r_l beyond which planetary formation is possible as a function of the binary mass ratio $q = m_2/(m_1 + m_2) = m_2$ (recall that $m_1 + m_2 = 1M_\odot$) and binary eccentricity e_B . The color coding is the following: -*Green*: $r_l \leq 4\text{AU}$ (the inner edge of our planetesimal disc) -*Pale blue*: $4\text{AU} < r_l \leq 6\text{AU}$ -*Dark blue*: $6\text{AU} \leq r_l \leq 9\text{AU}$ -*Red*: $9\text{AU} \leq r_l < 12\text{AU}$ -*Black*: $r_l \geq 12\text{AU}$ (the outer edge of our planetesimal disc) The radial distance given at the center of some rectangles is the minimum value beyond which *runaway* accretion is possible.

It can be seen that for equal mass stars (mass ratio $q = 0.5$) planet formation proceeds in all the regions of the disk and for all binary eccentricities. For smaller values of mass ratios and high binary eccentricities, the inner border for accretion shifts to larger radial distances. For $q = 0.1$ and $e_b = 0.5$, for example, planet formation can occur only beyond 10 AU. The strong secular perturbations due to the large eccentricity and low mass ratio of the binary prevent planetesimal accumulation closer to the barycenter. In most cases where accretion is possible, however, the growth path is probably not runaway since the perturbations of the binary lead to random velocities slightly higher than the escape velocities from the larger planetesimals.

4. Conclusions

Numerical simulations of planetesimal evolution support the scenario in which planet formation may undergo even in binary star systems. Planetesimals in both S-type and P-type orbits keep their relative velocities low enough to allow accumulation rather than fragmentation for a wide range of binary orbital and physical parameters even if orderly growth or the so-called Type II runaway growth (Kortenkamp et al. 2001) are possibly more common than the conventional fast runaway growth presumed to occur around single stars. Both terrestrial planets and giant planets are supposed to form in binary systems unless extreme orbital conditions for the two stars are met like large binary eccentricity or very short separation (in the case of circumprimary disks). The potential lower rate of planet discovery around double stars may be ascribed to these cases rather than to a general effect related to the presence of a companion star.

Acknowledgments.

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